Magnetization of HTS Cables for Accelerator Applications

Mike Sumption, *C. Kovacs*, *C. Myers*, M. Majoros, and E.W. Collings

Center for Superconducting and Magnetic Materials, MSE, The Ohio State University

U.S. MAGNET DEVELOPMENT PROGRAM

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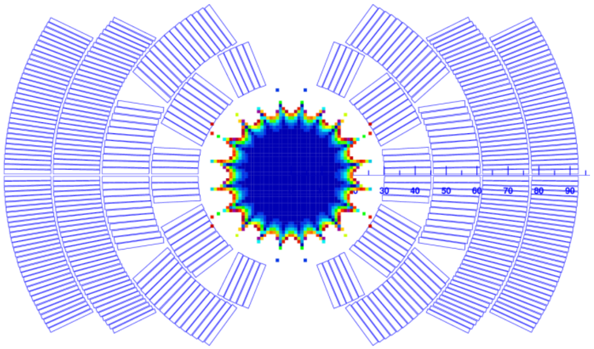
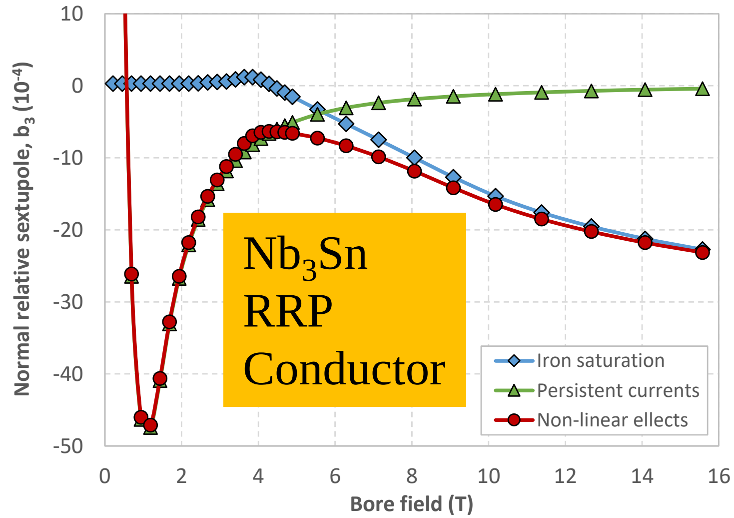
Outline of talk

- Motivation – accelerator quality
- Use of $\pm$ 3 T Dipole Magnetometer and 12 T Hall Probe Magnetometer for Measurement of CORC and Roebel cables
- Measurement Results – Comparison to each other and the base tapes
- Application to accelerators
- Magnetization Creep and Drift
- Next Steps …

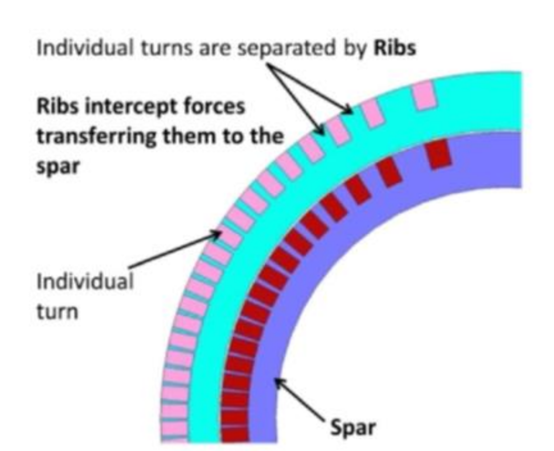
Motivation--Field Error in Accelerator Magnets



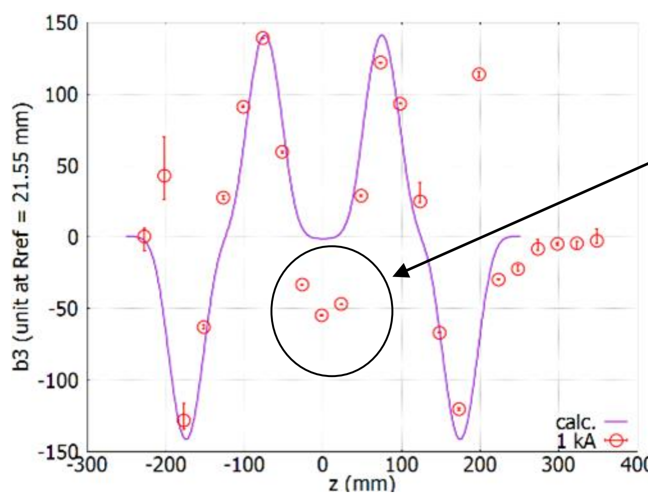
Cos theta



A Zlobin, “15 T dipole design concept, magnetic design and quench protection”, Presentation at the US MDP workshop Jan 2017



YBCO CORC Canted cos coil (Wang, LBNL 2018 MDP)

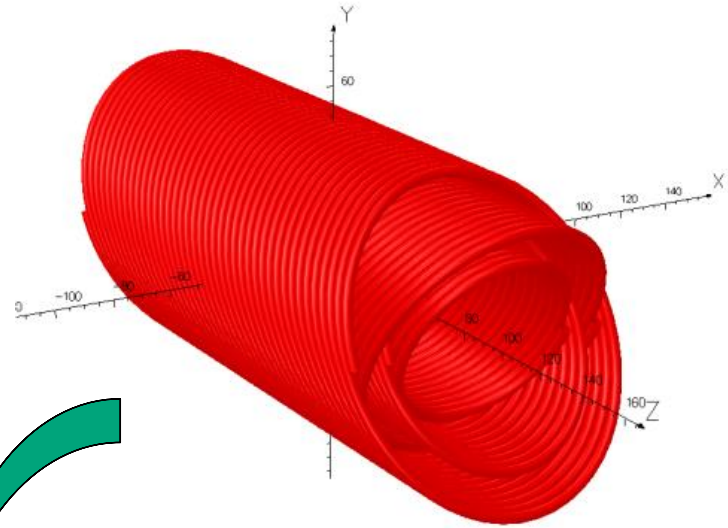


Magnetization related b3

Department of Materials Science and Engineering

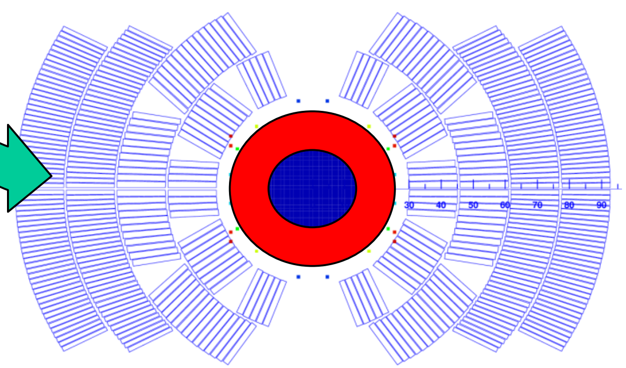
LBNL Collaboration Canted Cos Dipole studies

X Wang/LBNL working on canted cos dipole using YBCO cable



X. Wang, "REBCO accelerator magnet development: status and plans", Presented at the USMDP NAPA, Jan 2017

- As part of LBNL-OSU collaboration, Nb_3Sn magnetization measurements and Bi:2212 magnetization data have been provided for error field calculations in other magnet designs
- This collaboration is expanded to include YBCO conductor and cable magnetization for magnets, and collaboration on error field determination
- <u>**Cory Myers (OSU grad student) will perform a DOE grad student study program at LBNL working on field error**</u>



- If we consider for a moment the simplest case of an HTS insert in a background Nb_3Sn magnet, then at injection, it may be reasonable to approximate field on CCT as a "uniform 1 T"
- **Initial error estimates using biot savart (and a doublet approach) suggest significant b3 for CCT wound with YBCO cables, as expected extrapolating from CCT1 > 25 unit**

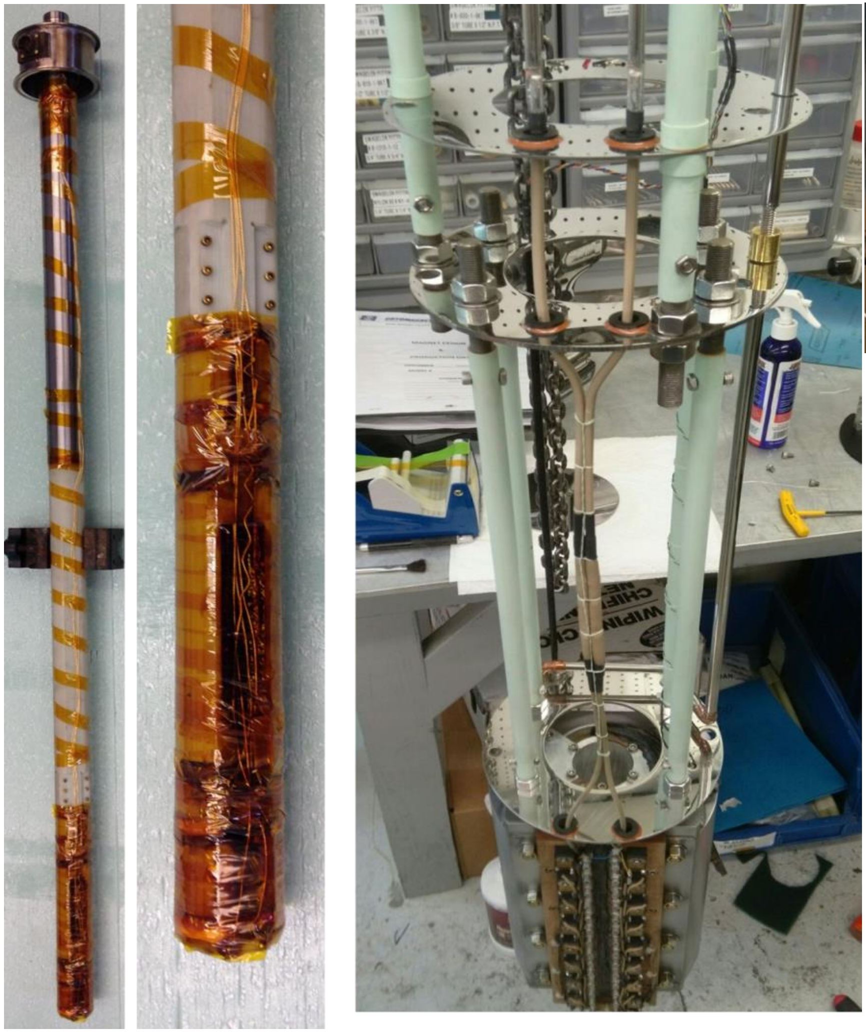
What do we want to know

- How big is the magnetization of HTS cables?
- How might that impact field error in magnets
- Is the creep of M substantial, and what impact might that have on field error
- Do we have models for M and Mcreep for HTS cables that can be used in calculations – and if not can they be made?
- How does pre-injection cycle modifications work on cables vs tapes – i.e., can we have predictive models?
- What about ICR and current sharing – can magnetization shed light on this?

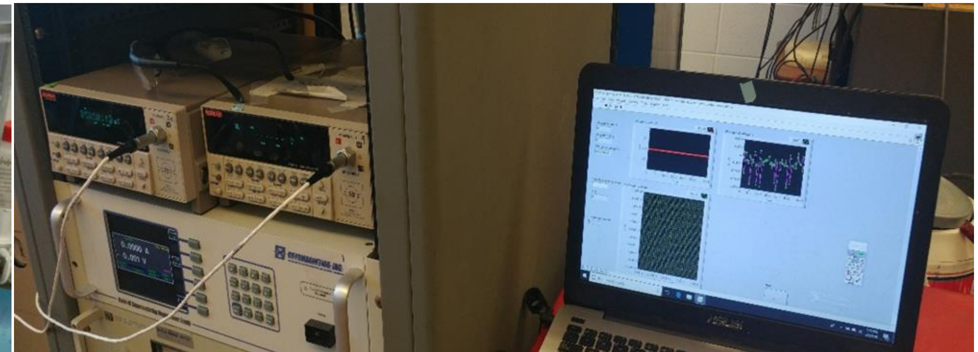
OSU Magnetic Measurement Systems

Magnetometer	**MAG-0: PPMS**	**MAG-1**	**MAG-2**	**MAG-3**
Temp., field ranges	1.9 K+, ±14 T	4.2 K+, ±12 T	4.2 K, ±3T	77 K, ±0.15 T
Measurement type	VSM Short samples Persistent current/creep	Pickup coil, Hall sensor Medium length samples Persistent current/creep + transport current	Pickup coil, Hall sensor Long (20 cm) cables Persistent current + transport current Coupling current	Pickup coil, mediun length samples, 77 I screening only
Sample materials	Nb_3Sn, Bi2212 strand YBCO tape (creep only)	HTS short cables YBCO tape	Nb_3Sn and HTS cables	YBCO

3 T Dipole Magnet Cable Magnetization System

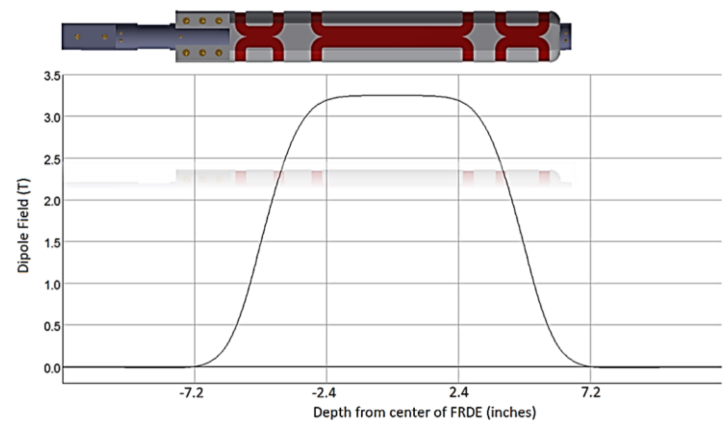


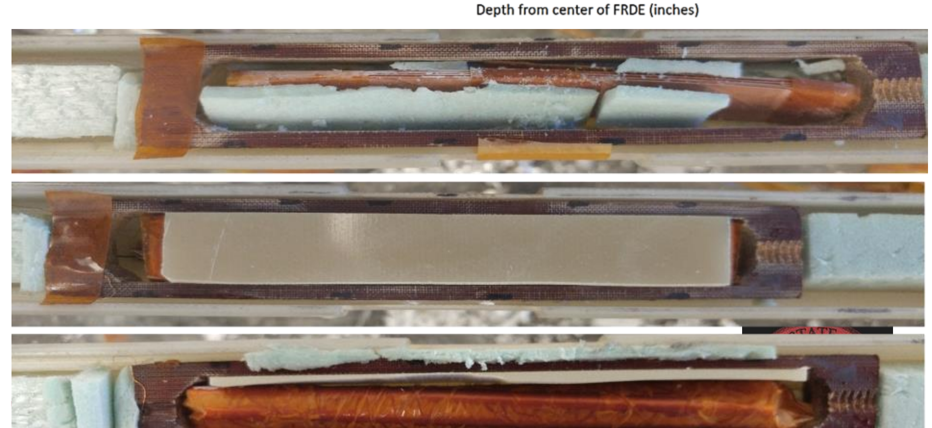
Sample holder, Pickup Coils, Dipole Magnet



Data Acquisition, Magnet Supply, Control Computer

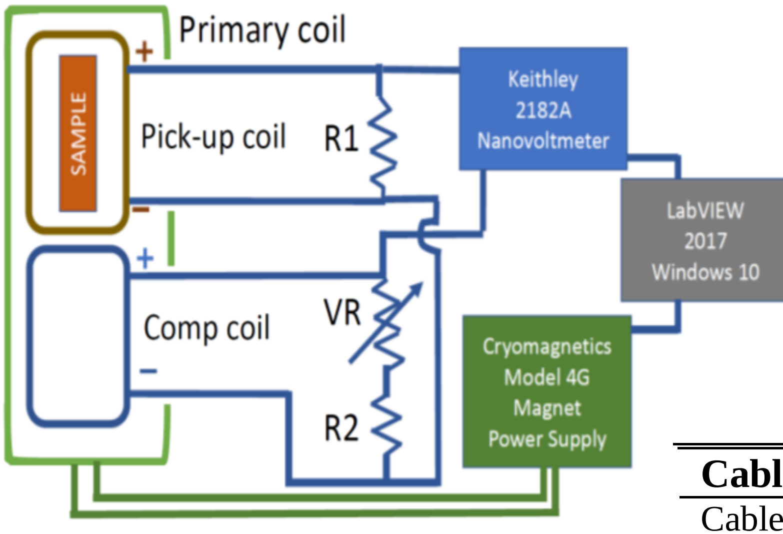
B = ± 3 T





Samples in pick-up coils

Cable Samples Measured



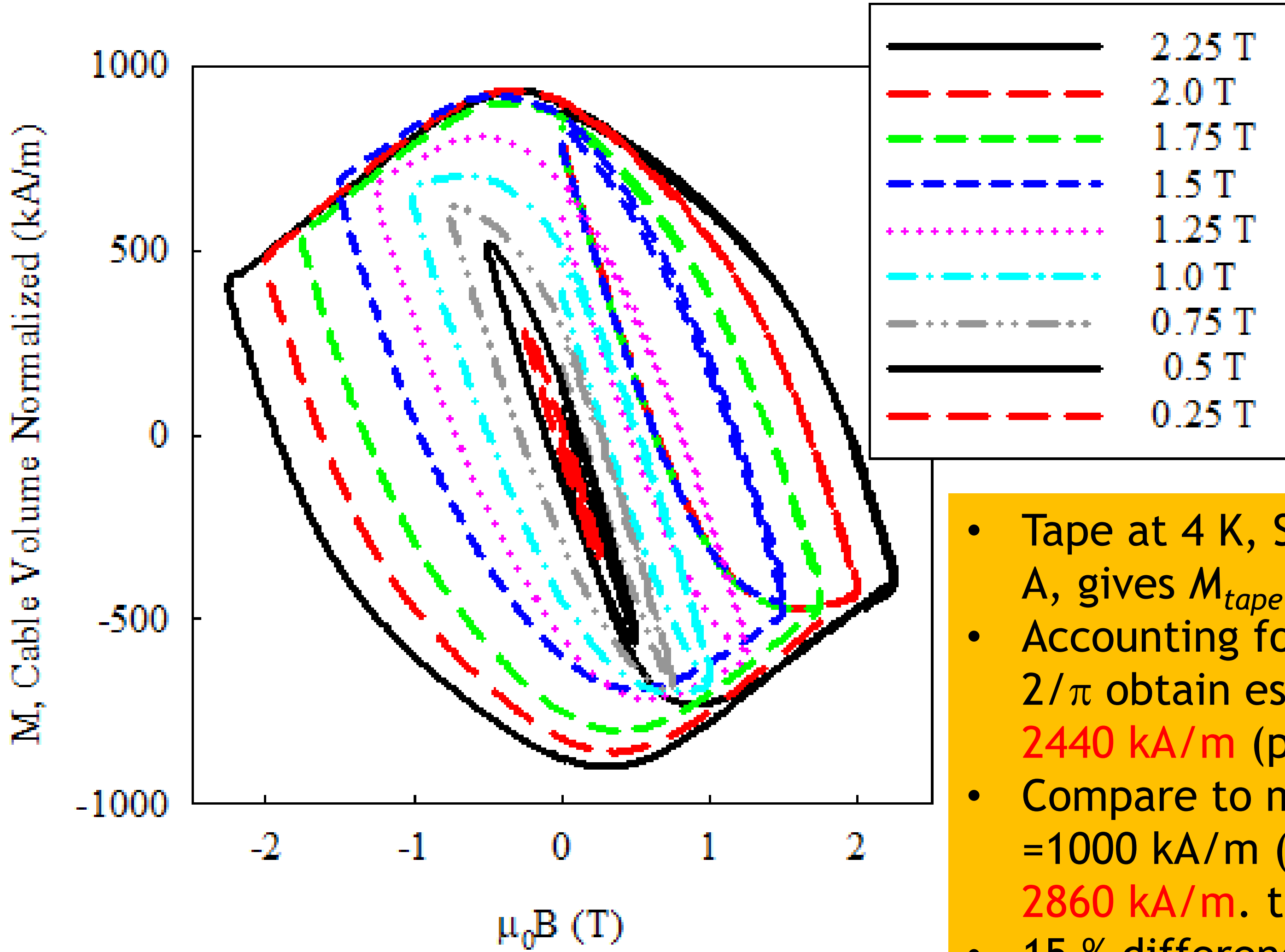
CORC: Provided by LBNL, ID 160823-Berkeley 250-C. Tape I_c = 69.5 A at 77 K, SF (16 tapes), cable I_c was 4.1 kA at 4 K; the cable was used for the canted cosθ dipole denoted C0a.

Roebel cable: KIT/ Super-Power tape, 77 K Ic = 1168 A for cable, giving 129 A per

Cable Properties	CORC™	Roebel
Cable dimension (mm)	3.21 (OD)	12 x 0.48
No. Tapes	16	9
Tape width (mm)	2	5.6
Tape thickness (mm)	0.045	0.096
Cable Pitch (mm)	6.22	126

Sample Properties	CORC™	Roebel
Sample Length (cm)	9.42	9.07
Number of segments	6	4
Pack Dimensions (mm)	10 (OD)	4.3 x 12
V_{cable} (cm^3)	4571	2089
V_{strand} (cm^3)	1591	1755

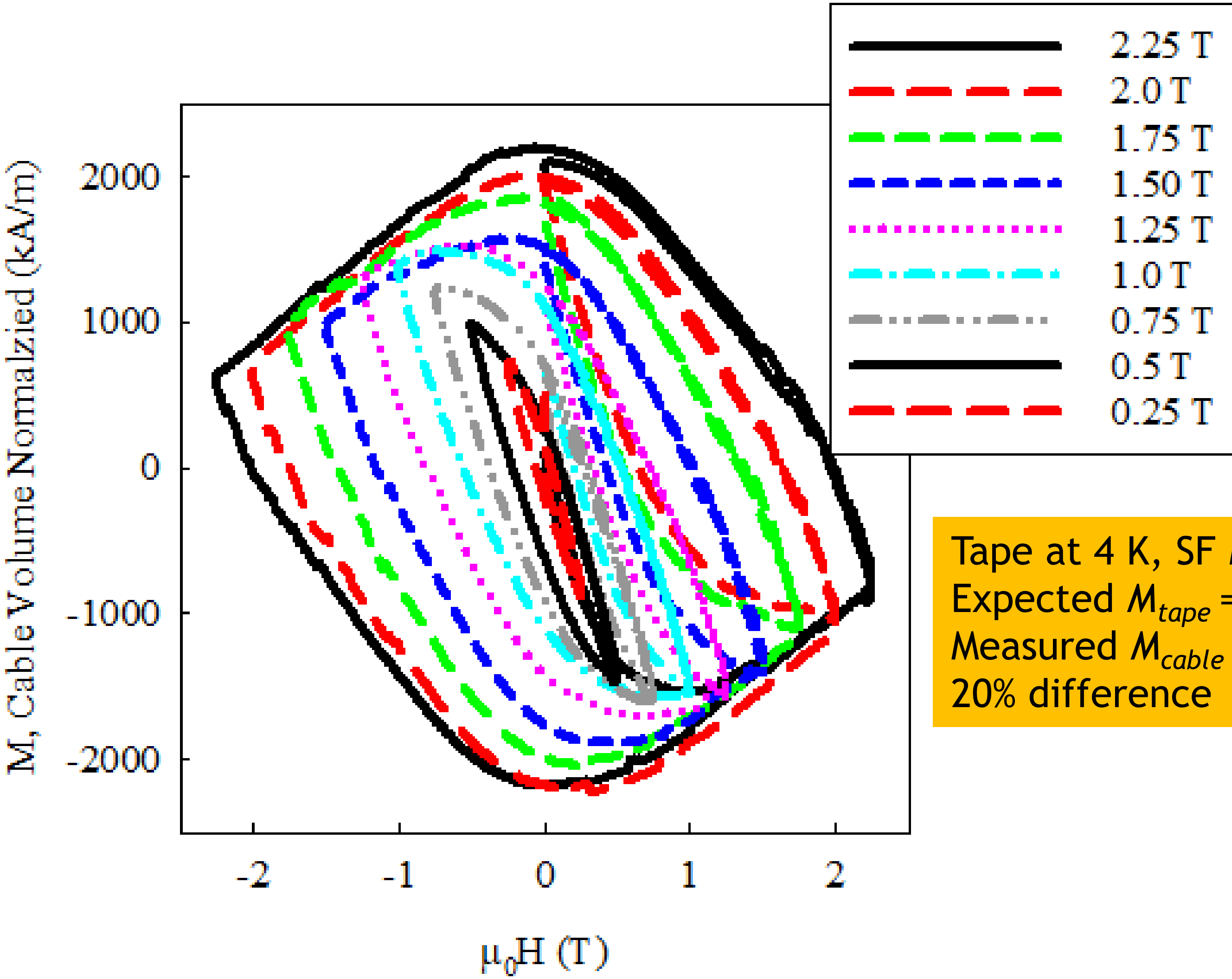
M-H Loops for CORC wire/cable (3 T Dipole)



- 4 K *M-H*
- $B_\perp$
- Normalized total cable volume

- Tape at 4 K, SF, estimated I_c = 690 A, gives $M_{tape} = J_c w/4$ = 3833 kA/m
- Accounting for helical twist, apply $2/\pi$ obtain estimate for CORC = 2440 kA/m (per tape vol)
- Compare to measured M_{CORC} (B=0) =1000 kA/m (cable Vol) X 2.86 = 2860 kA/m. tape vol
- 15 % difference

M-H Loops for Roebel Cable (3 T Dipole)



- 4 K M-H
- $B_\perp$
- Normalized total cable volume

Tape at 4 K, SF I_c =1290 A.
Expected M_{tape} = 3220 kA/m (tape vol)
Measured M_{cable} = 2640 kA/m (strand vol)
20% difference

CORC-Roebel Comparison

- For these particular cable samples, $M_{Roebel} \approx 2\ M_{CORC}$ (per cable vol)

- Filling factor of the Roebel cable is 84%, while that of the CORC is 35%, so $M_{Roebel,\ strand\ vol}$ = 2640 kA/m, while $M_{CORC,\ strand}$ = 2860 kA/m

- On the other hand, we might expect $M_{roebel,strand\ vol} \approx (1/2)\ M_{CORC,\ strand\ vol}$, since $M \sim J_c w = I_c/t$, while I_c values are similar, and $t_{Roebel} \approx 2\ t_{CORC}$

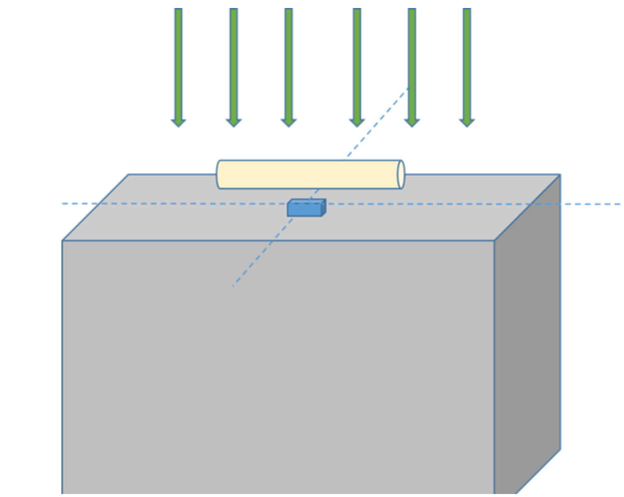
- But here we must again include the factor of $2/\pi$, suppressing this difference

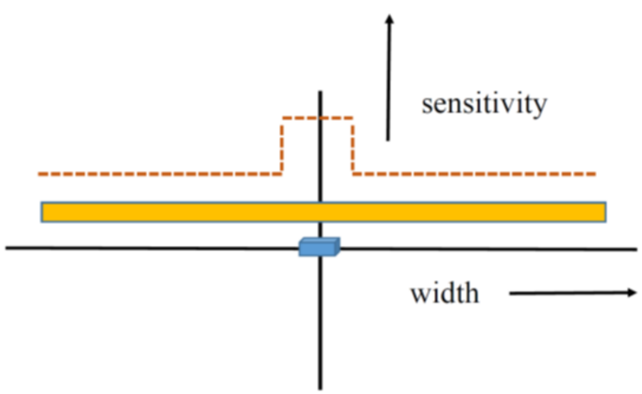
- These $M >> M_{LTS}$, for example the LHC NbTi conductor, with its Mh,cable,1.9K,0.54T $\approx$ 10.3 kA/m

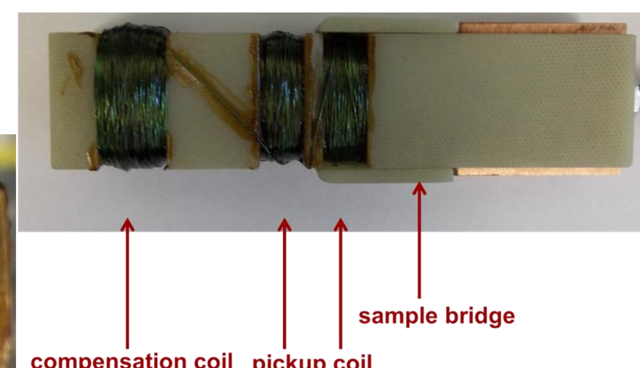
- Thus the use of HTS cables could lead to significant field errors, unless they are mitigated by variations of pre-injection cycles or other methods – let's look closer

12 T Hall Probe Cable Magnetometer

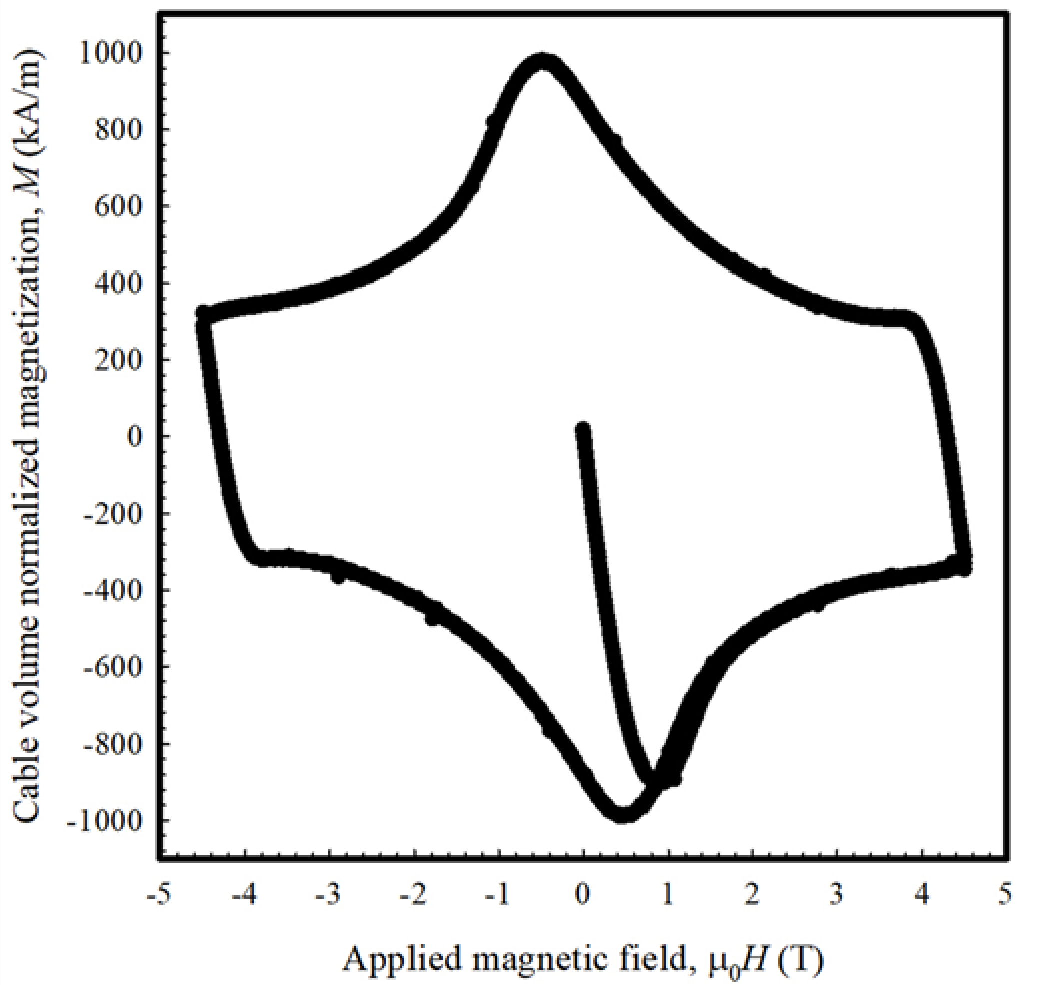
- Measurement made by ΔB between sample and no sample
- Field generated by 12 T, liquid cryogen free, RT bore magnet
- Cooling provided by varitemp dewar





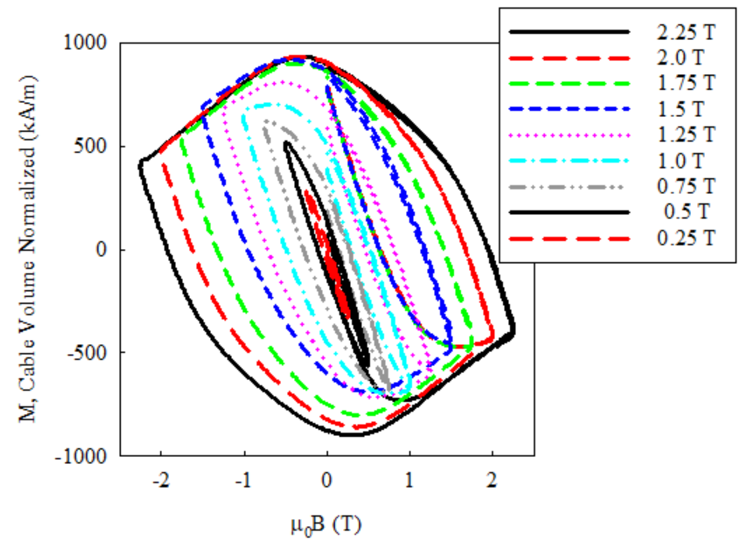


M-H of CORC ± 4 T, Hall probe



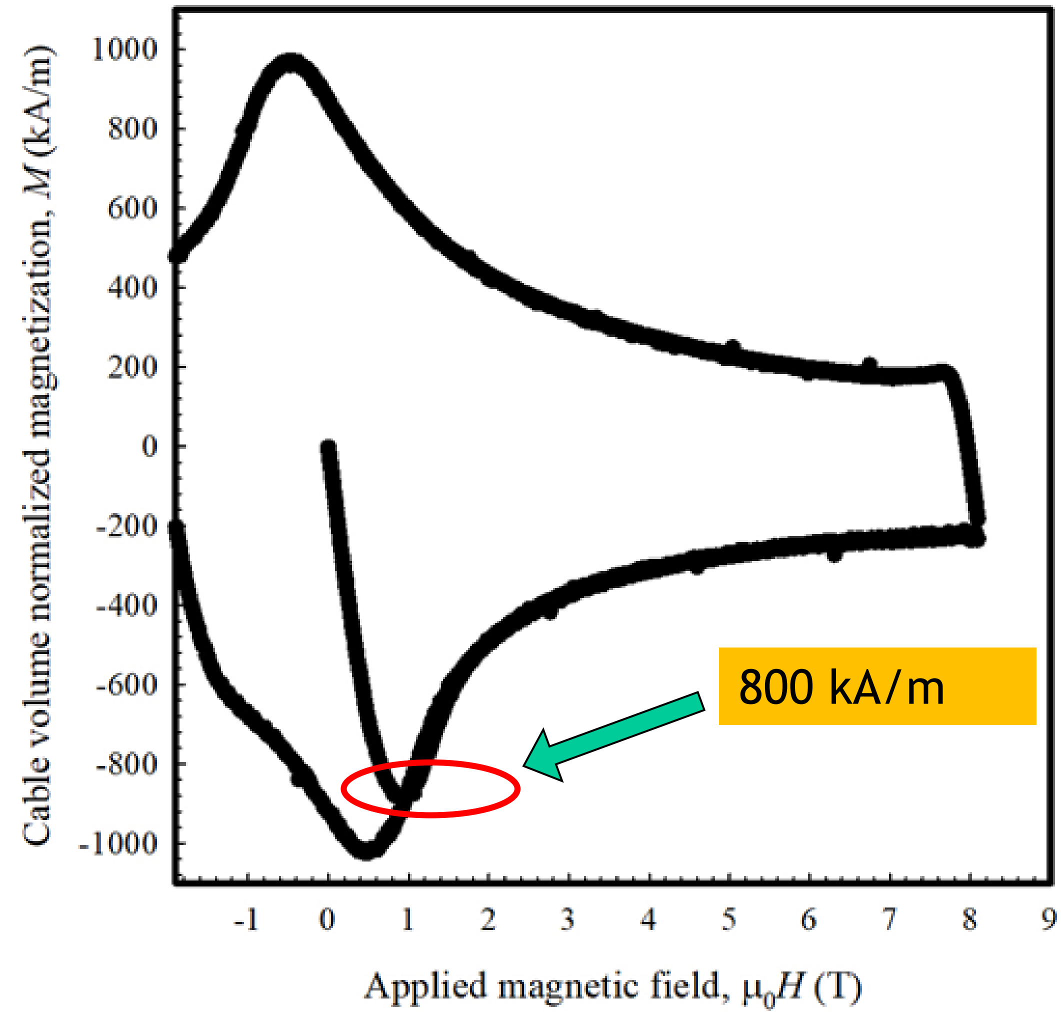
The Berkeley tape ID was 160823-Berkeley 250-C, used in their magnet C0a (Same as measured in 3 T dipole)

- 4 K M-H
- $B_\perp$
- Normalized total cable

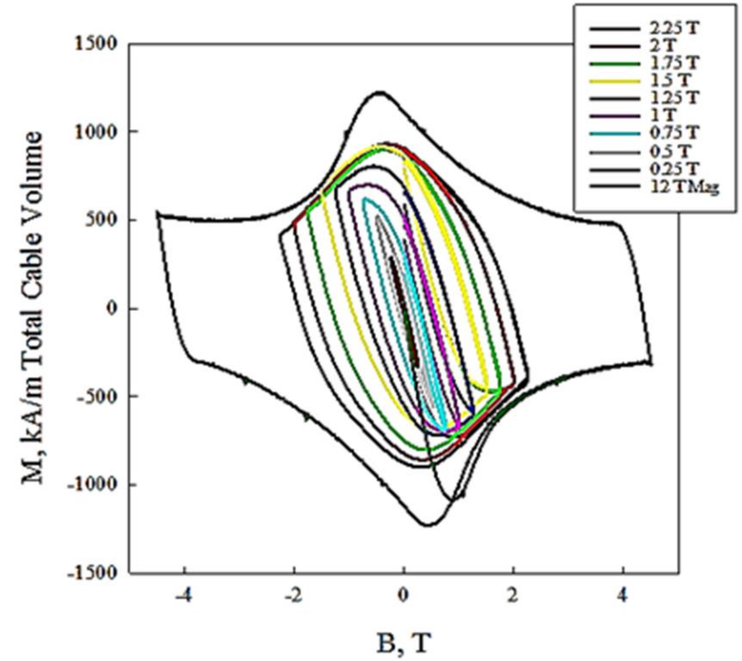


3 T Dipole

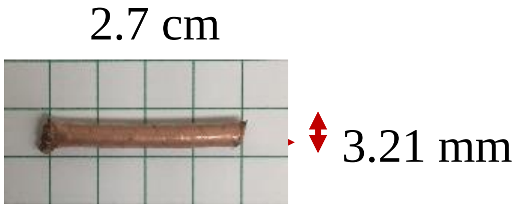
M-H of CORC -2 T to 8 T, Hall probe

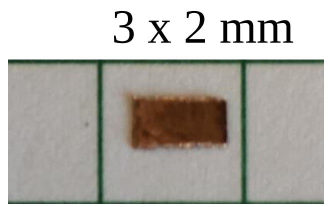


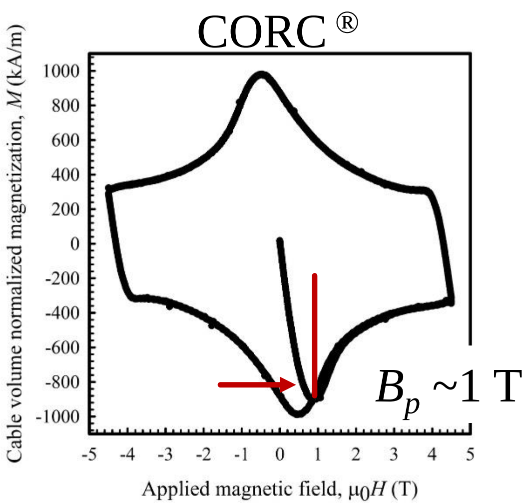
- 4 K *M-H*
- $B_{\perp}$
- Normalized total cable volume

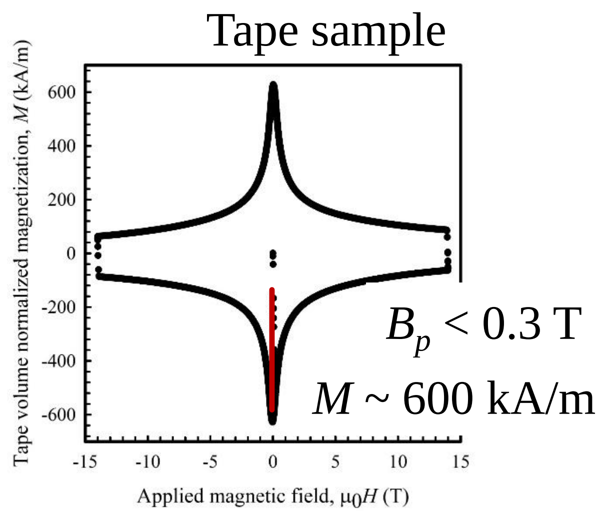


So, how is Cable Magnetization different than tape? Let's compare gross shape









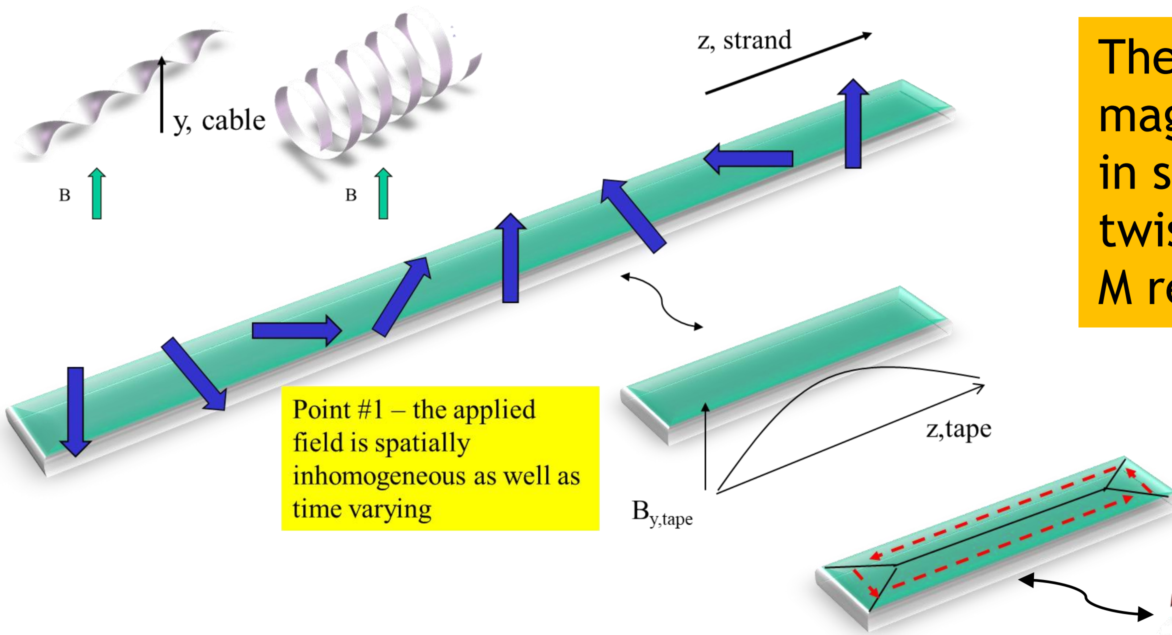
(1) FOR CORC, Mcable ~2/πMtape (tape vol norm)

(2) Penetration field is much higher in cabled sample

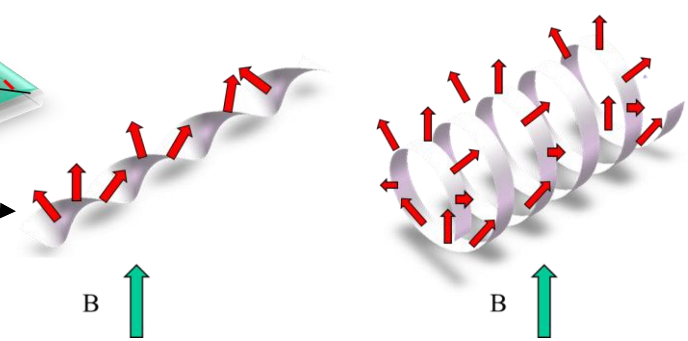
Answer:

1. **Magnetization** at full penetration is **similar**, but different by factors of **up to 2**
2. **Penetration field** for **Cables >> Tapes** (1 T as compared to 0.1 T)
3. Because of (2), (1) can be ***very different in tapes and cables in the area of interest (injection), depending on pre-injection cycle***

Why is Magnetization of CORC different than Tape?



The fact that the magnetization vector rotates in space due to the helical twist leads to a factor of 2/π M reduction



But, in fact the same helical twist induces short sample-like effects which also modifies M, leading to …

$$\Delta M = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{2y_m}{3L}\right) = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{w}{3\frac{L_p}{2}}\right) = \Delta M_0 \frac{2}{\pi}\left(1 - \frac{2w}{3L_p}\right)$$

Analytic Result!

OK …. So Why is the penetration field 10 X larger?

$B_p = \mu_0 J_{c,ybco} t_{ybco} = \mu_0 J_{c,ybco}(t_{ybco}/t_{tape})(t_{tape}/t_{ybco})t_{ybco}$
$= \mu_0 J_e t_{tape}$

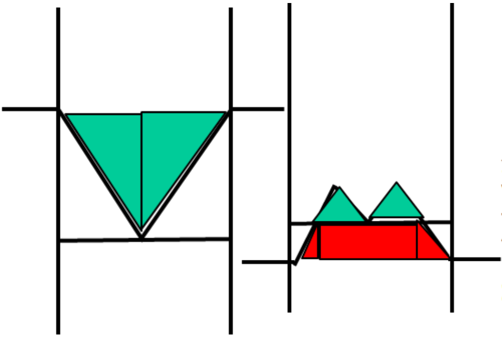
That is, is should sort of go up like the number of tapes …

If CORC has 8 layers, expect B_p to be 8 times larger on basis of above equation (so, 0.2T becomes 1.6 T)

But due to demag, $B_{edges} = 2\ B_{applied}$, thus $B_p = ½\ 1.6\ T = 0.8\ T$

OK, well how is this influenced by pre-cycle?

$$M = \frac{2}{\pi}\frac{J_c a}{2} FF \left[1 - \frac{w}{3L_{p,eff}}\right]\left[1 - \left(\frac{B - B_{min}}{B_p}\right)\right]$$



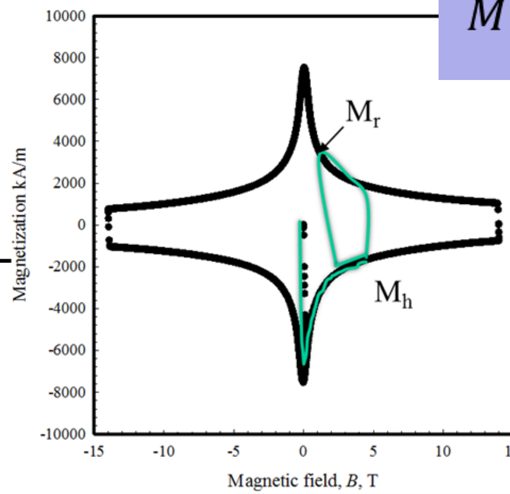
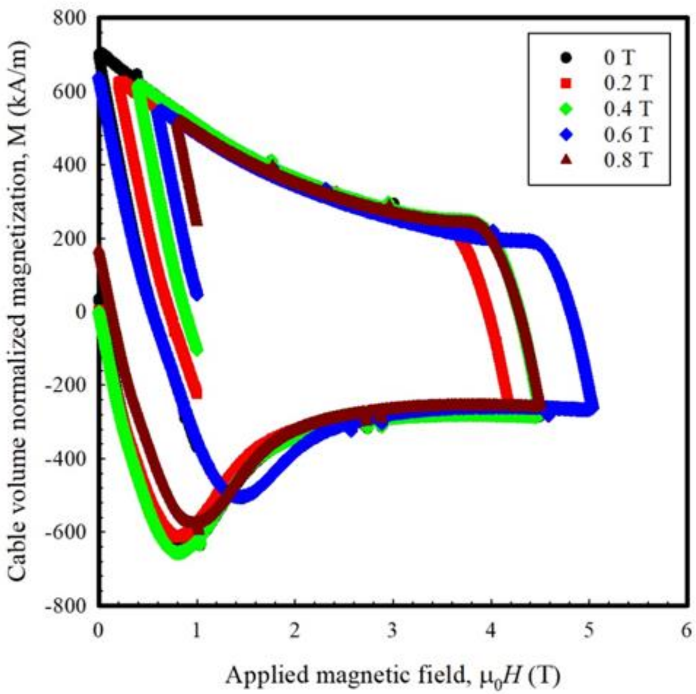


TABLE I
MAGNETIZATION AND DRIFT VALUES

Sample type and hold field	M_0 (kA/m)	*Mpred (kA/m)*
CORC 0 T	-430	-420
CORC 0.2 T	-280	-210
CORC 0.6 T	19	210
CORC 0.8 T	180	420

Can we now predict it? Yes!



What's the potential affect on field error in accelerators?

- Results not yet been put into field error calculations for magnets, will be magnet geometry dependent
- Nevertheless, some value for simply imagined "replacing" a NbTi or Nb_3Sn winding
- Taking the LHC as a reference, $b_3 \cong 3$, $M_{h,cable,1.9K,0.54T}$ = 10.3 kA/m
- Nb_3Sn d_{eff} 10 X that of NbTi, b_3 10 X higher $\cong$ 30-40 units.
- For HTS cable, $M_{inj} \cong$ 600-900 kA/m, suggesting b_3 values around **300 units** for a direct replacement (the current density at collision is roughly similar for these cables at their point of operation, so no correction is added for that).
- This is a very simple and rough estimate, and assumes no changes in the magnet to minimize these effects. As such, it is merely a starting point of data for inclusion in magnet design.

Drift on the injection Porch

REQUIREMENTS FOR REAL TIME CORRECTION OF DECAY AND SNAPBACK IN THE LHC SUPERCONDUCTING MAGNETS

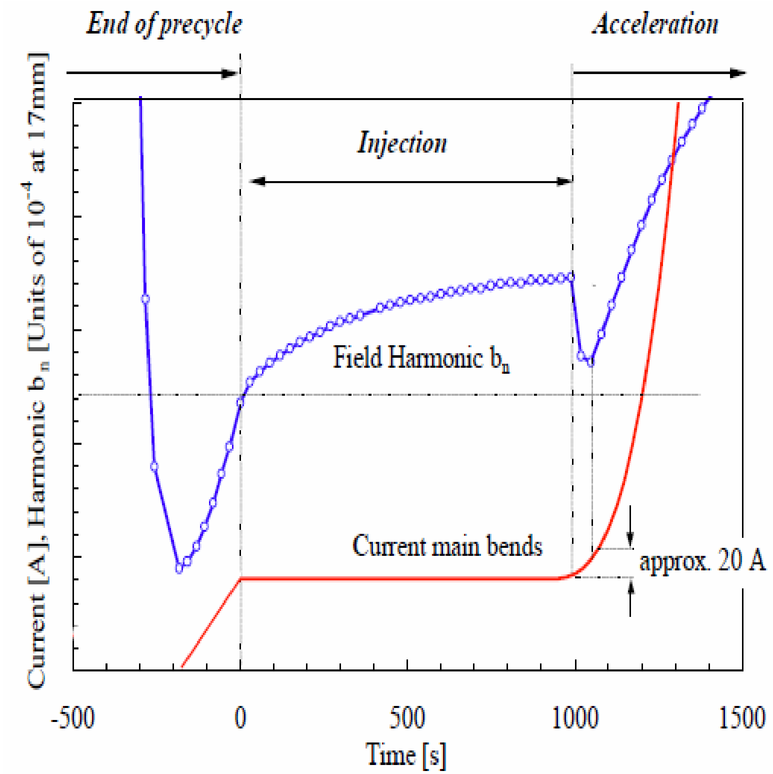
T. Wijnands, M. Lamont, A. Burns, L. Bottura, L. Vos,
CERN, Geneva, Switzerland

- Just as important as the absolute value of b_3 is any ***change with time*** during the injection porch

- It is possible to compensate for error fields with corrector coils, but the presence of ***drift*** makes this much more difficult

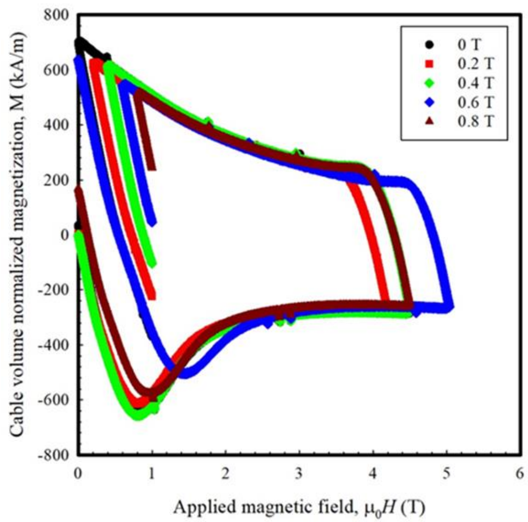
- At right is shown the drift of the error fields as a function of time from zero to 1000 seconds for LHC magnets, followed by a snap-back once the energy ramp begins

- The underlying mechanism for drift in NbTi magnets is the decay of coupling currents, (especially inhomogeneous and long length scale coupling currents) and their influence on the strand magnetization

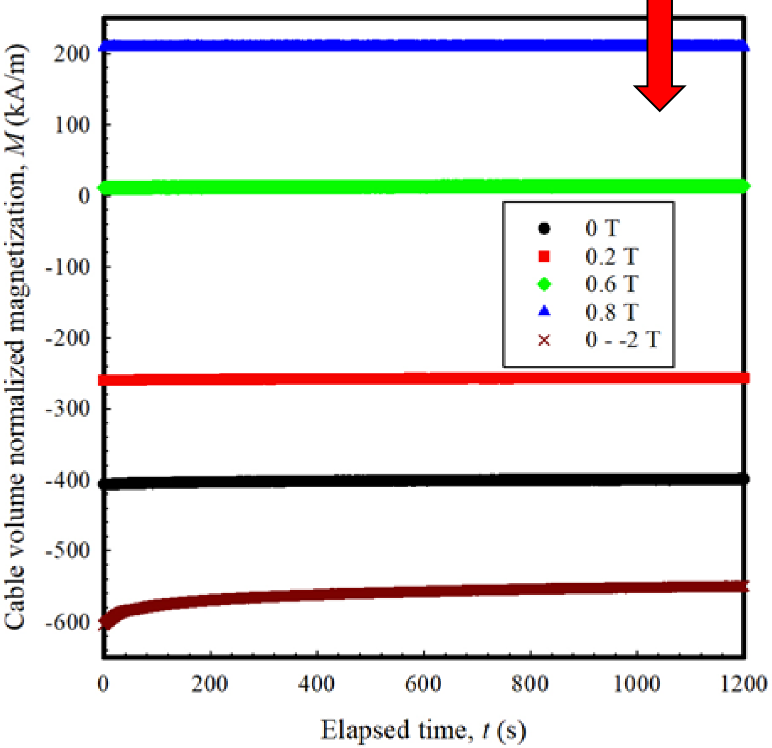


Need to keep both b_3 and its drift below 1 unit
For NbTi and Nb_3Sn based magnets, this is possible

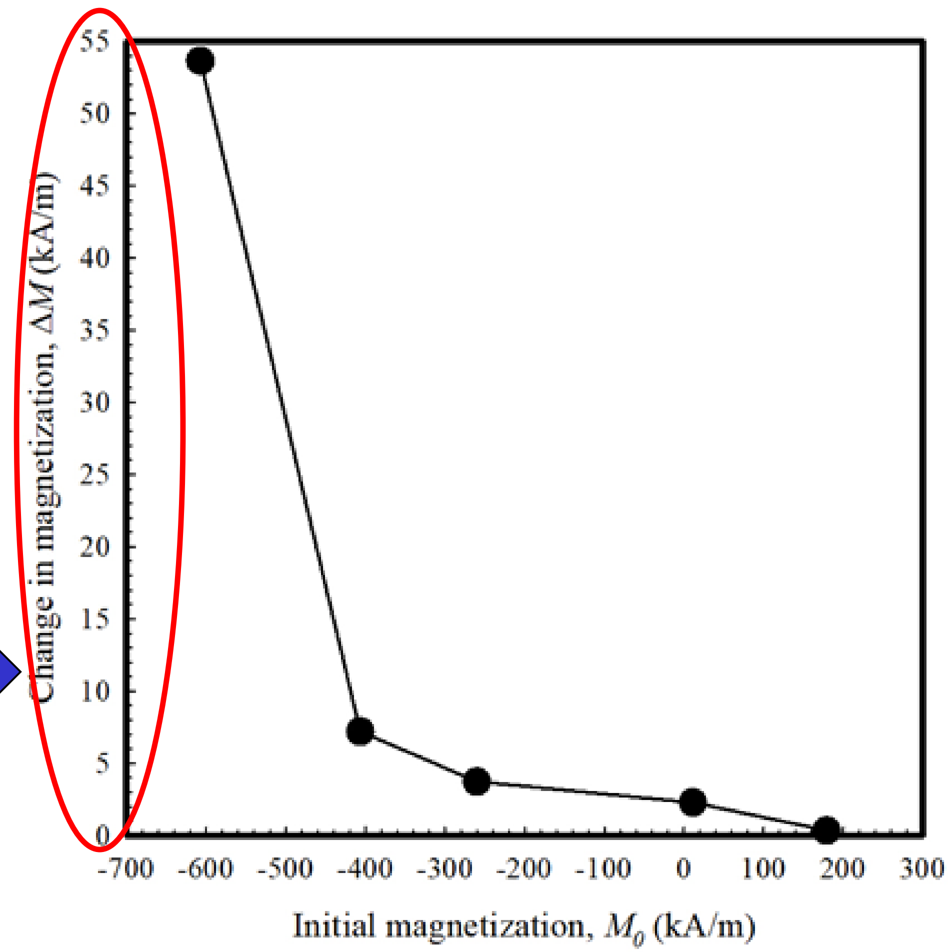
Substantial Drift/Creep in the M of HTS cables!



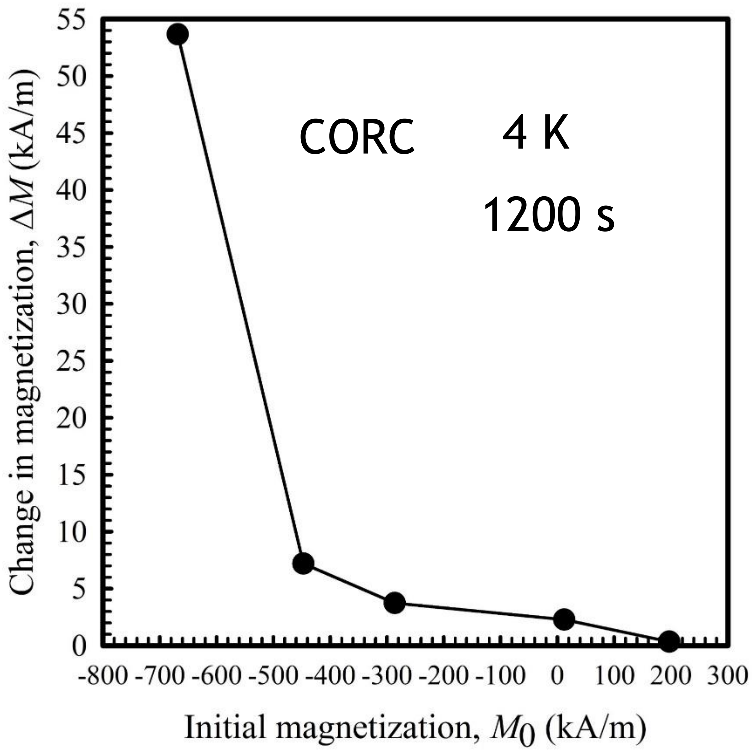
After our explorations of M vs pre-cycle, we looked at M creep vs pre-cycle

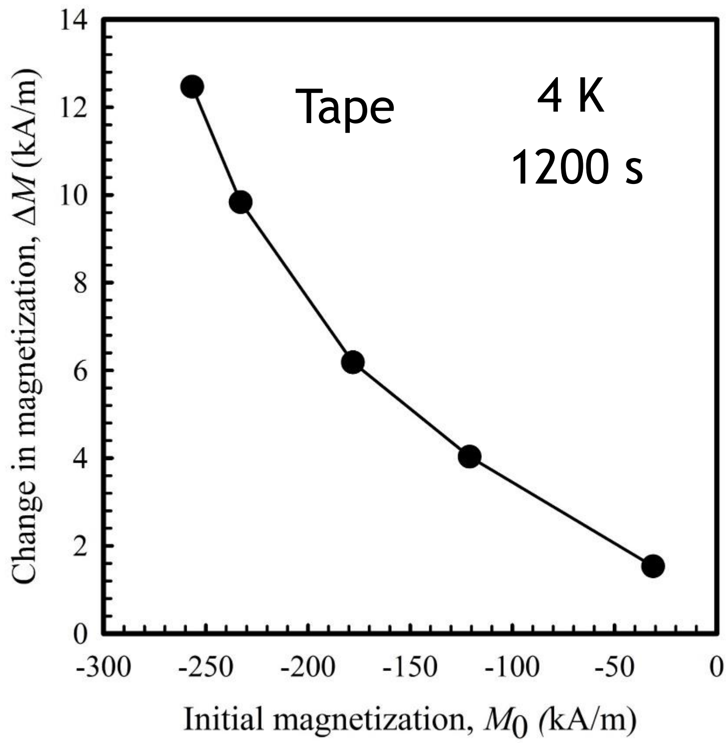


HTS materials suffer significant flux creep
Even at 4 K for precision applications!



Magnetization decay is different in tapes vs Cables – at least at injection – why?





- Magnitude of cable M is much larger for cable because of high B_p
- Magnitude of Creep is correlated with that
- **Creep (Change)** in HTS Cable M similar to **Absolute Value** of Nb_3Sn Magnetization

Next Steps I

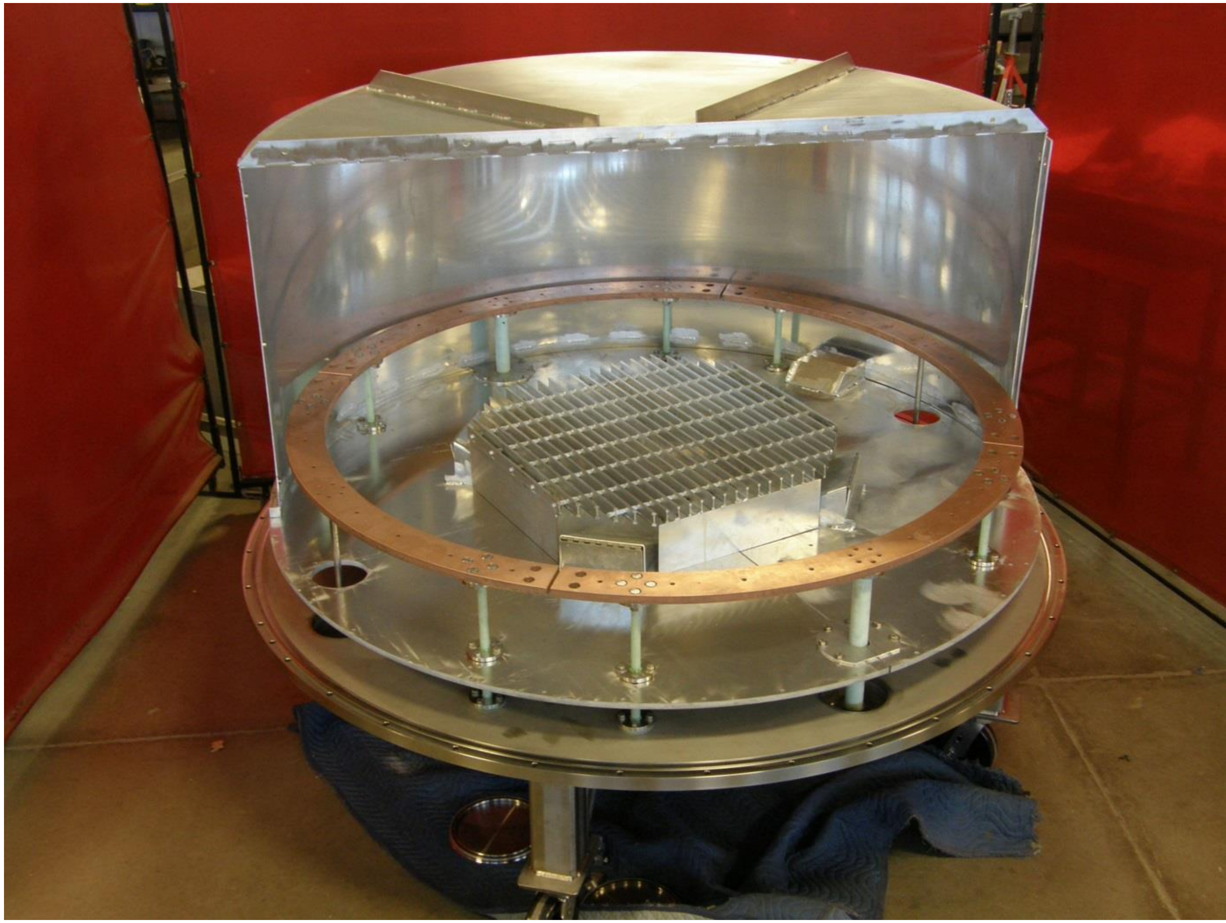
- Measurements shown **here** are quasi-static – allowing measurement of hysteretic ***M*** (persistent current Magnetization), and ***M decay***
- But, magnetization with higher ramp rates also allows the determination of coupling currents, which are of interest in terms of their contributions to M and Mdecay, but also serve as a measure of interstrand contact resistance, ***<u>and are a kind of proxy for cable current sharing</u>***
- ***<u>It is well known for LTS that low ICR implies good current sharing but lousy M, while high ICR, good M but lousy ICR</u>***
- ***Thus, ramp rate dependent measurements of cable M, planned for next steps, leads to the potential to explore pressure, preparation, and surface treatment on ICR and thus current sharing in HTS cables***
- **This work is being paired with direct current sharing and cable stability measurements in CORC and Roebel at OSU [Cryogenics Volume 95, October 2018, Pages 57-63]**
- <u>Also it is the focus of OSU grad student Chris Kovacs's DOE student fellowship at FNAL, where he is working with a Superconducting transformer</u>

Next Steps II – Magnetic Systems – planned upgrades

- Provision of sample current leads (5 kA) with a Lorentz force restraining sample holder for **dipole system** to enable a study of transport current modification to Mh at fields near "injection".
- Integration of a multiple-hall probe magnetometer in **dipole system**.
- The addition to **dipole system** of a low current (low field) but fast ramping power supply (field frequencies of up to 100 mHz albeit with a maximum field of 0.5 T) to enable the measurement of M_{coup}
- Installation of a susceptibility-sensor system to the **12 T Hall probe system**

Cryo-conduction system
-- of interest for higher T small HTS coil tests?

- Coils up to 1.5 m OD
- T down to 4 K
- 3 W at 4 K
- 1800 A current leads (but not at 4 K)



- Obtained on NIH funds, and being used for that purpose – but could bring value to some HEP tasks
- Will make available for use if of interest to do some prototype testing at higher T and/or conduction cooling of HTS HEP coils

Summary

- Two Magnetization Systems have been made and applied to measure HTS cables for Accelerator applications; (1) A 12 T hall probe system, and (2) a 3 T dipole system
- *M-H* measurements were performed using these systems on CORC and Roebel Samples
- Typical values were 1000-2000 kA/m (cable vol) or about 2500-3000 kA/m (tape vol), which is roughly 100 X that of NbTi or 20 X that of Nb_3Sn (10 kA/m and 50 kA/m respectively)
- Main differences between ***Tape*** and ***Cable*** were
  - High B, full saturation M *Similar* (but in detail different by up to $\approx$2X)
  - B_p 10 X larger
  - *M* at injection *significantly modified* because of nearness of B_p to B_{inj}
- Magnetization Creep was shown to be significant, with a *M*-change similar to absolute *M* of Nb_3Sn conductors
- Pre-cycle modifications (well known) can be used to reduce *M* and *M* drift (but there are limits to this)